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AUTHOR(S) A. Goldman, D. McGuire, and C. Croarkin

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Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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ASSIGNING MASS VALUES TO IN-HOUSE STANDARD UF_6 CYLINDERS

A. Goldman
Los Alamos National Laboratory
Group N-1, MS E540
Los Alamos, NM 87545
(505) 667-2402

D. McGuire
Rockwell International
Rocky Flats Plant
Golden, CO 80401
(303) 966-5252

C. Croarkin
U.S. Department of Commerce
Statistical Engineering Div.
National Bureau of Standards
Gaithersburg, MD 20899
(301) 975-2849

ABSTRACT

A statistical experimental design called the Fast 4-1 Series is used to assign mass values to in-house standard UF_6 cylinders. This design is intended to minimize the number of weighings of large cylinders yet provide acceptable estimates of mass values and their precision.

I. INTRODUCTION

The concept of relating a reference standard to another test object (known synonymously as check standard, working standard, secondary standard, or in-house standards, IHS) has been of concern in the nuclear industry. Specifically, a particular application is found in the UF_6 industry.

Production objects in the UF_6 industry are typically large steel cylinders filled with nuclear material and having gross weights of about 15 tons. We suspected that scale loading procedures and air buoyancy corrections were potential error sources during calibration with industry standard iron weights.[2] To overcome these, a series of six replica mass standards (RMSs) were fabricated to duplicate the geometry, displacement, and approximate mass of the UF_6 cylinders in use by the nuclear industry.[1]

Duplicate cylinders of each of three sizes were prepared--one filled with stable materials to a total weight approximately equal to the gross (full) weight and one left empty to approximate the empty (tare) weight of production cylinders.

Table I lists the RMSs and uncertainties that were established in 1977 by the National Bureau of Standards (NBS).

The RMSs serve as reference standards for the introduction of the SI unit (international system of units) for mass into the mass measurement process at UF_6 shipping/receiving locations nationwide. Each of these locations maintains its own group of IHSs, which are also replicas of production cylinders.

This paper deals with estimating parameters that are associated with the IHSs. Experimental designs are given for situations that involve

TABLE 1

REPLICA MASS STANDARDS

RMS Designation	UF_6 Cylinder Design	Mass Value (lb)	Mass Value (kg)	Total Uncertainty (lb)	Total Uncertainty (kg)	Displacement Volume (ft^3)
RMS 1 (empty)	30B	1 126.238	511.123	0.130	0.059	29.59
RMS 2 (full)	30B	6 355.999	2 883.033	0.138	0.063	29.89
RMS 3 (empty)	48X	4 461.909	2 024.750	0.138	0.063	120.75
RMS 4 (full)	48X	25 332.124	11 490.4[illegible]9	0.188	0.085	121.38
RMS 5 (empty)	48Y	5 284.926	2 397.202	0.138	0.063	154.67
RMS 6 (full)	48Y	32 507.502	14 745.156	0.214	0.097	154.67

some common measurement processes. These designs and the procedures presented here are applicable to any set of objects for which the RMS is known and the IHS is to be determined. A detailed general description is given by Croarkin.[2]

II. ASSUMPTIONS

The Fast 4-1 Series method is used to assign mass values to the IHSs. This method, one of many least-squares techniques that are acceptable for quantifying an IHS, has been adopted from NBS Test Report 213.09/G 43216/UCC-1.[3] The Fast 4-1 Series defines a type of experimental design that consists of four weighings of known standards and four additional weighings of test objects.

The IHSs for a particular facility have mass values assigned to them according to a procedure having the following characteristics:

- The RMSs are the standards of mass measurement used (for example, mass values assigned by the NBS).
- The weighing device is operated in the comparative mode by a "null" reading method. In this method a particular output value of the comparator is selected with one of the weights of interest on the deck or platform of the weighing device. This value is reproduced for each observation by the addition or removal of small weights to or from the device.
- The value recorded for each observation is the sum of the small weights added to the device to obtain a null value.

To satisfy these characteristics, we assume that weighing devices are available with the required capacity and sensitivity. The magnitude of the RMS should be nearly equal to that of the IHS. A preliminary mass value should be obtained by directly weighing the IHS.

We assume that the "reproducibility" of the weighing device is determined before the Fast 4-1 Series is run, where the standard deviation is obtained as a measure of reproducibility. The suggested stepwise procedure for obtaining the measurements is as follows:

(a) Place a cylinder (IHS or RMS) on the device.

(b) Establish a null value by placing small standard weights on the device until its output reading is near midrange.

(c) Record the sum of these added weights.

(d) Remove the cylinder from the device.

(e) Repeat steps (a) through (d) from 5 to 10 times keeping the time between successive executions of step (a) as nearly equal as practical. Reproduce the null value as closely as possible.

(f) Compute the standard deviation of the measurements. If the standard deviation is too large, the weighing instruments and the process should be thoroughly checked and corrected before proceeding.

Sometimes the same value is obtained for each measurement and the standard deviation is 0. In this case of perfect reproducibility, the sensitivity of the device may be obtained by adding additional small weights until the null changes. "Sensitivity" is defined as the magnitude of the weight required to change the null. Sensitivity can be compared with the uncertainty to be assigned the IHS. As a guideline, an acceptable sensitivity is less than 10% of the maximum acceptable uncertainty of the IHS.

III. THE FAST 4-1 SERIES

The following sequence is a Fast 4-1 Series in which the facility has one RMS and two IHSs:

Observations	Weight
O_1	Certified standard (RMS)
O_2	$(IHS)_1$ Weight to be calibrated
O_3	$(IHS)_2$ Weight to be calibrated
O_4	Certified standard (RMS)
O_5	Certified standard (RMS)
O_6	$(IHS)_2$ Weight to be calibrated
O_7	$(IHS)_1$ Weight to be calibrated
O_8	Certified standard (RMS)

Motivation for this and subsequent scenarios is given by L. W. Doher, P. E. Pontius, and J. R. Whetstone.[4] The measurement sequence and model are defined by

$$O_1 = R + b + e_1 ,$$

$$O_2 = b + x_1 + e_2 ,$$

$$O_3 = b + x_2 + e_3 ,$$

$$O_4 = R + b + e_4 ,$$

$$O_5 = R + b + e_5 ,$$

$$O_6 = b + x_2 + e_6 ,$$

$O_7 = b + x_1 + e_7$, and

$O_8 = R + b + e_8$,

where x_1 denotes $(IHS)_1$, x_2 denotes $(IHS)_2$, R denotes the "known" RMS, b denotes the bias of the weighing device, and e is a random variable distributed independently normal with mean 0 and variance σ^2.

A least-squares solution gives the following estimates of the parameters b, x_1, x_2, and σ^2:

$$\hat{b} = \frac{(O_1 + O_4 + O_5 + O_8)}{4} - R \ ,$$

$$\hat{x}_1 = \frac{-(O_1 - 2O_2 + O_4 + O_5 - 2O_7 + O_8)}{4} + R \ ,$$

$$\hat{x}_2 = \frac{-(O_1 - 2O_3 + O_4 + O_5 - 2O_6 + O_8)}{4} + R \ ,$$

and

$$\hat{\sigma}^2_1 = \frac{\Sigma(O_i - \hat{O}_i)^2}{5} \ ,$$

where $\hat{O}_i$ is the estimate of O_i found by using the least-squares estimates of the parameters (for example, $\hat{O}_1 = R + \hat{b}$).

The variances are given by

$\sigma^2 \{\hat{b}\} = 0.25\sigma^2_1$,

$\sigma^2 \{\hat{x}_1\} = 0.75\ \sigma^2_1$, and

$\sigma^2 \{\hat{x}_2\} = 0.75\ \sigma^2_1$.

For two RMSs and two IHSs, the sequence and design are defined by

$O_1 = R_1 + b + e_1$,

$O_2 = b + x_1 + e_2$,

$O_3 = b + x_2 + e_3$,

$O_4 = R_2 + b + e_4$,

$O_5 = R_2 + b + e_5$,

$O_6 = b + x_2 + e_6$,

$O_7 = b + x_1 + e_7$, and

$O_8 = R_1 + b + e_8$,

where R_1 and R_2 are known.

A least-squares solution is given by

$$\hat{b} = \frac{(O_1 + O_4 + O_5 + O_8)}{5} - \frac{R^*}{2} \ ,$$

$$\hat{x}_1 = \frac{-(O_1 - 2O_2 + O_4 + O_5 - 2O_7 + O_8)}{4} + \frac{R^*}{2} \ ,$$

$$\hat{x}_2 = \frac{-(O_1 - 2O_3 + O_4 + O_5 - 2O_6 + O_8)}{4} + \frac{R^*}{2} \ ,$$

and

$$\hat{\sigma}^2_2 = \frac{\Sigma(O_i - \hat{O}_i)^2}{5} \ ,$$

where $R^* = R_1 + R_2$.

The variances are given by

$\hat{\sigma}^2 \{\hat{b}\} = 0.25\ \hat{\sigma}^2_2$,

$\hat{\sigma}^2 \{\hat{x}_1\} = 0.75\ \hat{\sigma}^2_2$, and

$\hat{\sigma}^2 \{\hat{x}_2\} = 0.75\ \hat{\sigma}^2_2$.

The following design incorporates one RMS, two IHSs, a term for linear drift in the weights, and a check standard. The check standard, denoted by C, could be an RMS or some other weight. This work closely follows the approach used by Cameron and Hailes.[5] We assume that the linear change is caused by temperature effects. These measurements would be taken over a long period of time (for example, one measurement per week).

The model is given by

$O_1 = R + b + e_1 - 7\Delta$,

$O_2 = x_1 + b + e_2 - 5\Delta$,

$O_3 = x_2 + b + e_3 - 3\Delta$,

$O_4 = C + b + e_4 - \Delta$,

$O_5 = C + b + e_5 + \Delta$,

$O_6 = x_2 + b + e_6 + 3\Delta$,

$O_7 = x_1 + b + e_7 + 5\Delta$, and

$O_8 = R + b + e_8 + 7\Delta$,

where Δ represents the temperature effect, an unknown parameter.

The estimates of the parameters are given by

$$\hat{b} = \frac{(O_1 + O_8)}{2} - R \quad ,$$

$$\hat{x}_1 = \frac{(-O_1 + O_2 + O_7 - O_8)}{2} + R \quad ,$$

$$\hat{x}_2 = \frac{(-O_1 + O_3 + O_6 - O_8)}{2} + R \quad ,$$

$$\hat{C} = \frac{(-O_1 + O_4 + O_5 - O_8)}{2} + R \quad .$$

$$\hat{\sigma}^2_3 = \frac{\Sigma(O_i - \hat{O}_i)^2}{3} \quad , \text{ and}$$

$$\Delta = \frac{1}{168}(-7O_1 - 5O_2 - 3O_3 - O_4 + O_5 + 3O_6 + 5O_7 + 7O_8) \quad .$$

The variances for model 3 are

$\sigma^2(\hat{b}) = 0.5\hat{\sigma}^2_3$,

$\hat{\sigma}^2(\hat{x}_1) = 0.5\hat{\sigma}^2_3$,

$\sigma^2(\hat{x}_2) = 0.5\hat{\sigma}^2_3$,

$\hat{\sigma}^2(\hat{C}) = \hat{\sigma}^2_3$, and

$\sigma^2(\hat{\Delta}) = \sigma^2_3/168$.

Over a "long" period of time, other errors may appear in the design model. For example a random error on the RMS would give

$$O_i = (R + \delta) + b + 7\Delta + e_i \quad ,$$

where δ is distributed with mean 0 and variance σ_δ^2. Changes would be required in the estimation of parameters and their variances.

Matters and models such as these are left for further study.

EXAMPLE

Consider the previous model and the following measurements:

O_1 = 25 325.907	O_5 = 25 333.901
O_2 = 25 326.663	O_6 = 25 335.427
O_3 = 25 329.579	O_7 = 25 336.512
O_4 = 25 332.165	O_8 = 25 340.242

R = 25 332.076

The estimated parameters (±1 standard deviation) are given as follows:

$\hat{b}$ = 0.9985 (±0.1285)

$\hat{C}$ = 25 332.034 (±0.1817)

$\hat{x}_1$ = 25 330.589 (±0.1285)

$\hat{\sigma}_3^2$ = 0.0330

$\hat{x}_2$ = 25 331.504 (±0.1285)

Δ = 1.005 (±0.0172)

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